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Design for an Improved Head-Mounted Display System

Phase I Final Report

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12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.		12b. DISTRIBUTION CODE
13. ABSTRACT (Maximum 200 words) There is a requirement for head-mounted display (HMD) technology from within the military to train individuals in an immersive 3D environment. Angular field-of-view (FOV), image quality, and comfort are among the most important factors affecting the user experience in these applications. During the Phase I work effort, the NVIS team assessed the current state-of-the-art among available HMD products. NVIS, together with the University of Central Florida, created a feasible HMD design that would achieve a minimum FOV of 100 degrees across by 65 degrees vertically with a clear, bright image. This HMD was designed to maintain a reduced form-factor that best accommodates the target application - an urban combat training system that requires users to move quickly and operate a simulated rifle within the virtual environment. A successful Phase II program will deliver a working prototype based on our Phase I design, and set the stage for Phase III commercialization. The ultimate goal of this project is to productize the concept of a wide FOV HMD that can penetrate applications throughout DOD and the private sector by delivering an ergonomically designed immersive display with compelling image quality while remaining mindful of important economic factors to encourage widespread adoption of this technology.		

14. SUBJECT TERMS

STTR REPORT, Head-Mounted Display, HMD, Immersive, Virtual Reality, VR, Close Quarter Combat, CQB, training, simulation

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1. Technical Objective

The phase I effort is primarily aimed at performing a feasibility study for improving upon the current commercially available Head Mounted Display (HMD) technology. Specifically, a state-of-the-art HMD should be designed that serves the need of training war-fighters for close quarter battle (CQB) in a simulated immersive environment by providing a wider field-of-view (FOV), better image quality (resolution, contrast, color, linearity), good ergonomics, safety and reliability. The HMD should be lightweight, well balanced, stable and should have a form-factor that enables the combatant to train with a rifle and allows functions like running and rapid head movements in all directions. Since these specifications also suit many high demanding professional applications, the HMD should be commercialized at a reasonable cost.

Based on the currently available microdisplay, and the initial study that was carried out while preparing the Phase 1 proposal, following design objectives were set for the new head mounted display:

- >100° horizontal FOV, ~50° vertical FOV
- < 3 arcmin / pixel, full color
- High contrast, brightness
- Less than 1 kg.

2. Challenge

It is difficult to design a general purpose HMD that is fit for all applications. However, if the application and/or users are known beforehand, it helps in setting the design standards and specifications for the HMD. This project targets CQB training (currently being developed at the US Naval Research Laboratory) that is highly demanding. As stated above, this requires parameters such as wide FOV, high resolution, image linearity, light-weight, well balanced and low cost.

While it is desirable that these parameters co-exist, several of them act against each other. FOV directly affects optical resolution. Arcminute per pixel gives a measure of optical resolution as this quantifies the angle subtended by a display pixel on the eye. The larger the angle the coarser (lower) is the resolution. For a given FOV and a display source, arcmin/pixel can be calculated as shown in Figure 1. It is clear that for a given display, the larger the FOV the lower the optical resolution.

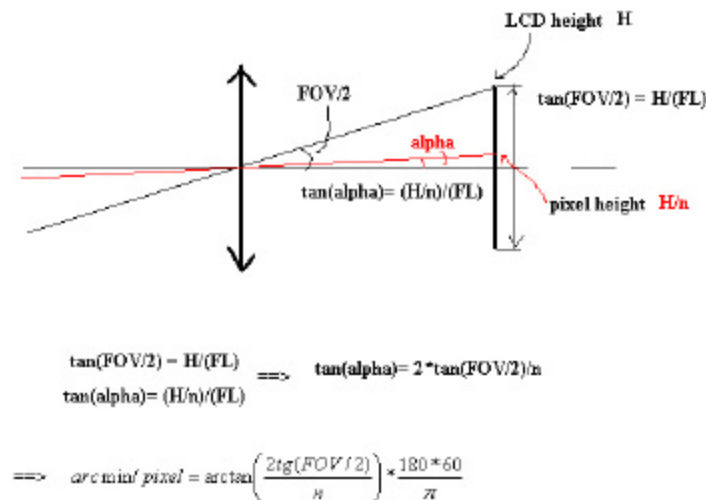


Figure 1. Calculation of arcmin/pixel for optical resolution

Where n is the number of pixels. Also, as the FOV is increased for a given display, the system starts exhibiting more and more aberrations that includes image distortion (non-linearity). Correcting the system for these aberrations becomes more challenging at larger FOV. The correction of this aberration typically requires additional optics that also means additional housing, hence more weight and cost. And depending upon the optical layout, it might also mean shifting the center of gravity of the system away from the user's head-center. Thus compromising balance. It can be seen that if there is one parameter that adversely affects all the other parameter for a given display, it is the FOV.

3. Approach

The approach to this project is inspired from the basic concept of combining pancake optics with a relay lens to obtain a large FOV, long eyerelief system. The conventional form of this approach has been limited in previous designs by a typically bulky and heavy relay lens system. Since most of these optics end up in front and top of the user, it make the system extremely front heavy and not fit for long-term wear. Since Dr. Rolland has been actively researching new diffractive optical elements (DOEs), lightweight plastic components, to develop a new projection engine for use as a replacement for eyepieces in traditional head mounted displays, it became quite apparent to evaluate the use of projection optics with pancake optics. The primary objective here was to reduce the weight and bulk of the conventional relay as far as possible while maintaining the fundamental capability of a pancake system to provide large FOV and long eye-relief. Preliminary study corroborated this concept. The HMD developed based on this new hybrid concept is referred to as "Pancake-Projection HMD" or PPHMD.

4. Work Completed

4.1 Microdisplay Evaluation

Given the application of this HMD, NVIS, Inc. identified early on that it must consider microdisplays with at least 1280x1024 addressable, full-color pixels per eye for this project. Ideally the chosen microdisplay will be compact, lightweight, and have low power requirements. For minimum FOV requirements, the microdisplay should have at least a 0.75" diagonal.

Based on this need, and the current availability of such microdisplays, NVIS chose a 0.88" diagonal SXGA (1280 x 1024 pixels) FLCOS (Ferroelectric Liquid Crystal on Silicon) reflective microdisplay. The microdisplay generates an SXGA resolution image with 24-bit color depth, on a 20.3mm x 18.5mm backplane with an active display area of 17.4mm x 13.9mm. The interface electronics accepts SXGA VESA standard graphics input in either analog or DVI digital video formats. The electronics drive the microdisplay via a Low Voltage Differential Signaling (LVDS) link. This enables the displays to be driven at a distance of up to 4m (currently 2.5m) from the main interface electronics (7.5m distance is currently being tested). See Table 1 for detailed specifications of the microdisplay.

4.2 Optics

The starting point of the PPHMD optical design is the conventional model of the pancake-relay optical system (explained later on in section 7.1 and Figure 21). The conventional relay is replaced by lightweight projection optics and the layout is optimized for the FLCOS microdisplay.

Figure 2 shows the folded optical layout of the monocular channel of the PPHMD. It consists of three parts: pancake optics, projection optics "leg" and the microdisplay illumination system. The conventional implementation of illuminating a front-lit microdisplay is with a beamsplitter rectangular prism. The prism in front of the microdisplay redirects the light from a source to illuminate the display. The illuminated microdisplay image is then slightly magnified via the projection optics so an image is formed close to the pancake optics. The pancake optics forms

the final image with a large FOV. The eye-relief is optimized to 23 mm to allow users with eyeglasses.

A large 17mm round pupil results by introducing a high gain (i.e. sharp as opposed to a Lambertian) thin diffuser placed close to the pancake optics where the intermediary image of the microdisplay is formed by the projection optics. In the absence of the diffuser, a rectangular 12mm x 10mm exit pupil is formed.

Based on the discussions with NRL, an overlap angle of 60° is set for the PPHMD. This results in an impressive size of the binocular overlap region where stereoscopic viewing.

For this configuration the FOV is optimized for the given microdisplay to monocular 80° horizontal and 68° vertical. Considering 60° overlap, the binocular FOV is 100° (H) and 68° (V) vertical.

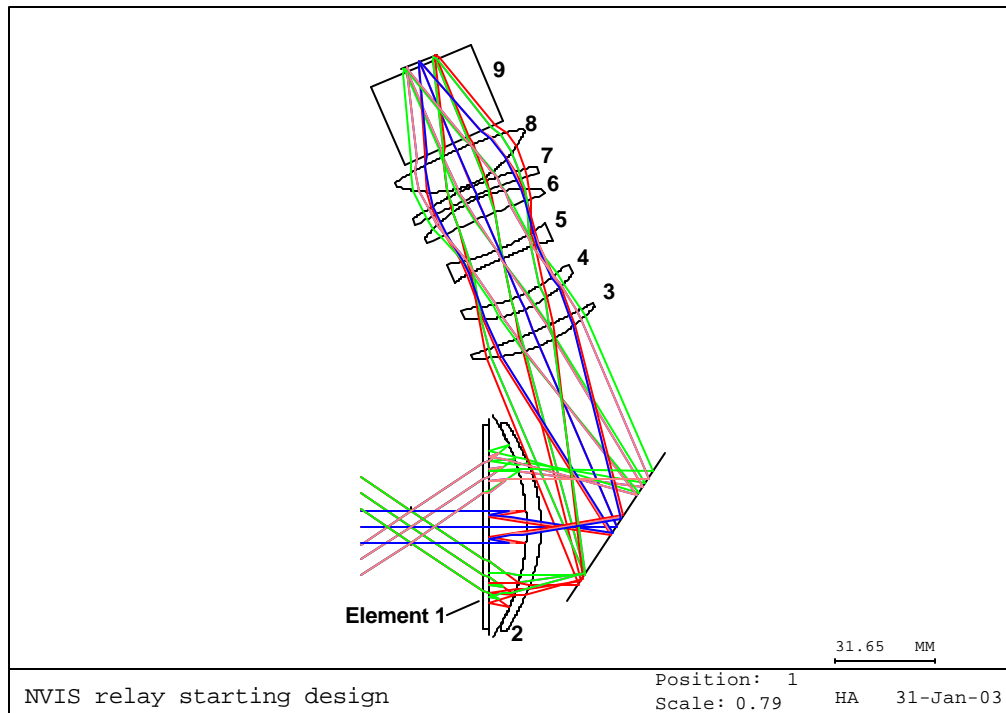


Figure 2. Folded optical layout for the PPHMD

4.3 Mechanical Design

Optical and mechanical teams worked together to satisfy each others design needs to come up with a solution that best meets the objective of the project.

The primary mechanical design criteria were:

- To keep the overall weight below the proposed 1 Kg (2.2 Lb).
- To keep the Center of Gravity (CG) of the overall system as close to the center of the head as possible for better balance and to minimize fatigue during use.
- To provide necessary mechanisms in the HMD, such as Interpupillary Distance adjustment, and other adjustments that are required to allow the user to adjust the HMD for optimal viewing.
- To control the form-factor of the HMD so that it can be effectively used for the targeted CQB application.

Figure 3 shows the PPHMD in its final design form for Phase 1. The optical layout shown in Figure 2 was the starting point of the actual mechanical design work. Figure 4 shows the CAD representation of the optical layout.

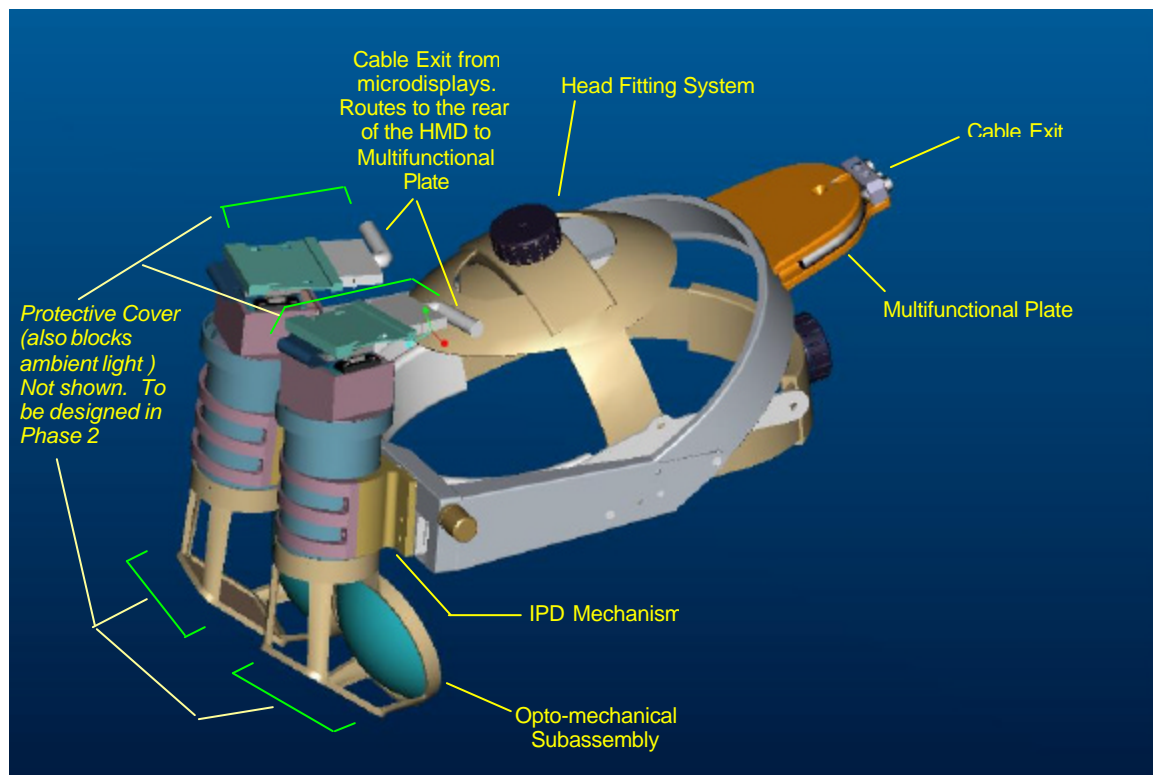


Figure 3. Pancake Projection HMD (PPHMD) phase I design.

The mechanical design is further subdivided into four major tasks:

- A. Design of various opto-mechanical housings to hold optical elements, microdisplay, and Illuminator in place.
- B. Design of various necessary mechanisms
- C. Design of Head fitting system and main body of the HMD
- D. Miscellaneous design including cable routing, strain relief, tracker mounting, etc.

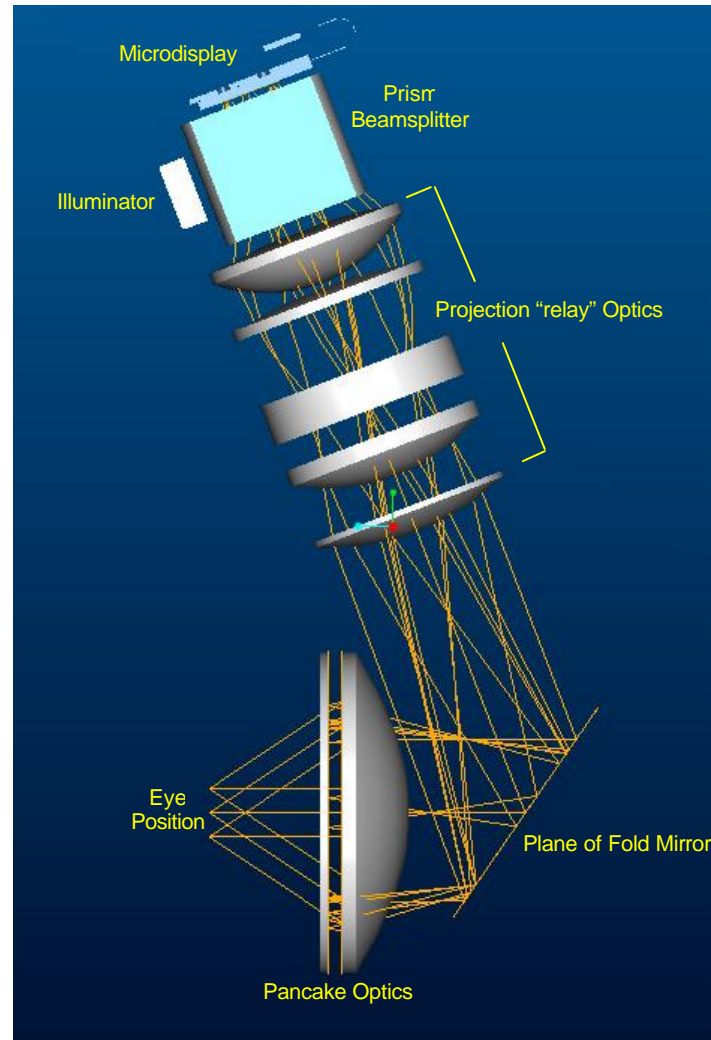


Figure 4. CAD representation of optical layout.

The design of these major components is discussed in detail below with associated figures. The figures also list the materials selected for various mechanical components keeping in mind the strength-to-weight ratio and ease of manufacturing. As shown, for most structural parts, Polyetherimide (PEI or ULTEM®) is chosen. ULTEM® keeps its hardness and mechanical properties from -40°F up to temperatures of 356°F. It is radiation-resistant and is naturally flame-retardant. Glass reinforced grades have even higher mechanical strength and exceptional strength-to-weight ratio. Because of its properties, it is the ideal replacement for steel and other metals. Typical density of 30% glass-filled (maximum reinforcement available) is 0.55 lb/in³ compared to Aluminum with 0.98 lb/in³. This means a weight saving of at least 40% over Aluminum.

4.3.1 Opto-mechanical Design

Figure 5 shows the exploded view of the opto-mechanical module with various mechanical housings for optics and microdisplay. The optical fold angle and the fold layout was decided to make the form-factor suitable for the CQB training that uses a rifle and keeping in mind that the CG of the system should be as close to the center of head as possible.

4.3.2 Design of Mechanisms

In practice, not every adjustment is required or even desirable. Each mechanism adds a level of complexity for both the manufacturer and the user. Simpler systems cost less, have fewer failures, and are easier to use. To save weight and cost and to keep the design simple, only necessary mechanisms are designed:

IPD

The design of IPD mechanism is implemented using off-the-shelf crossed roller slides. These are precision slides and carriage mechanisms that perform smooth linear motion with accuracy, 0.0001"/inch of travel, and repeatability, 0.0001 inches. Crossed roller provides improved stiffness and rigidity, effectively support overhanging loads. Figure 6 shows the IPD module. The left and right optical channel can be independently adjusted with the help of knobs that turn a custom-machined screw-shaft (made out of Aluminum) on either side for accurate alignment of optics with the user eye. Figure 7 shows the exploded view of the same mechanism to illustrate the component level.

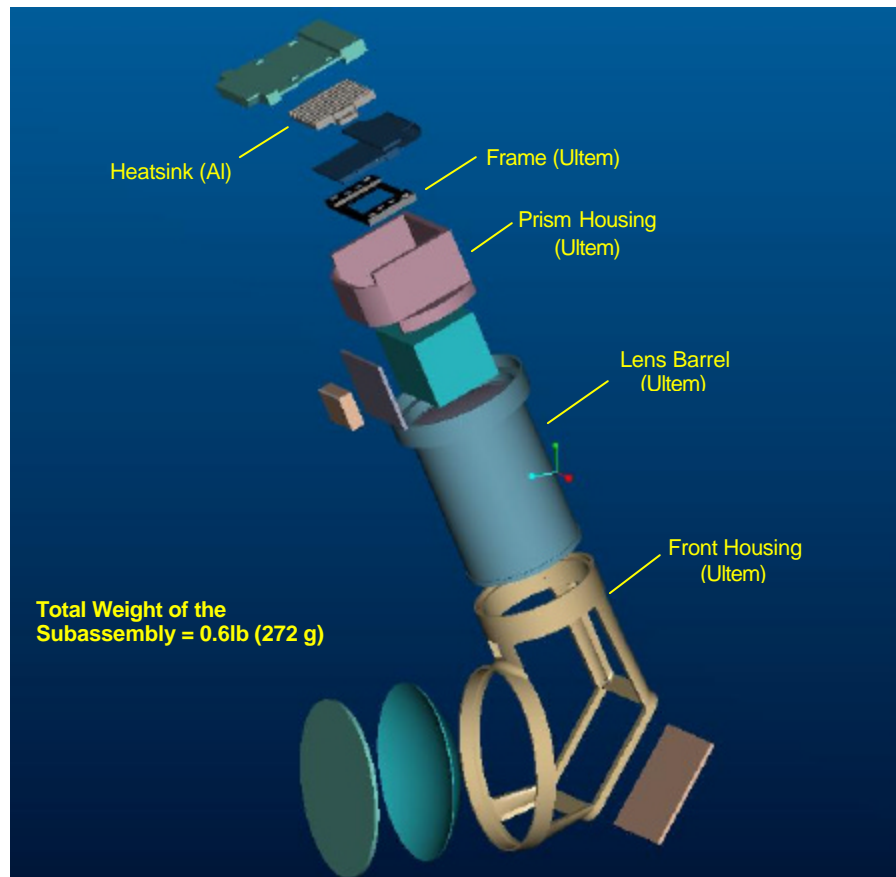


Figure 5. Exploded view of the monocular opto-mechanical module.

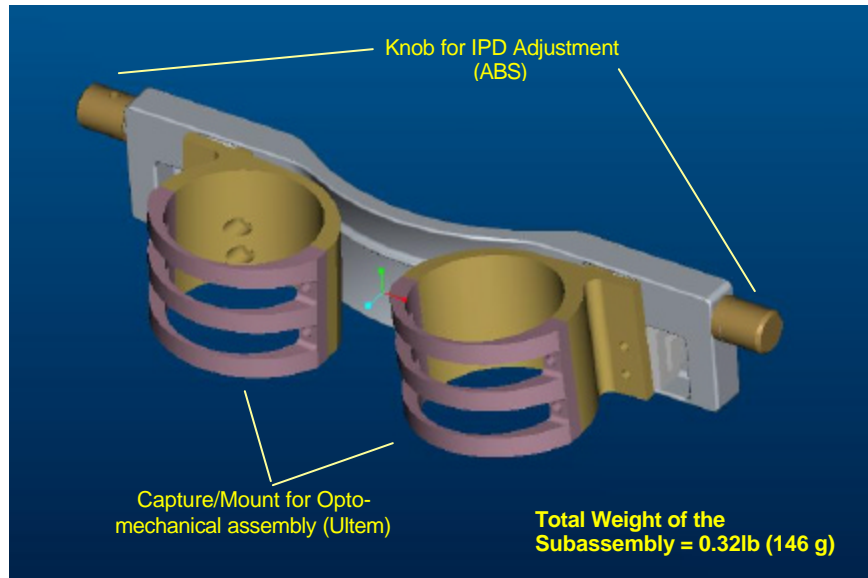


Figure 6. Exploded view of the monocular opto-mechanical module.

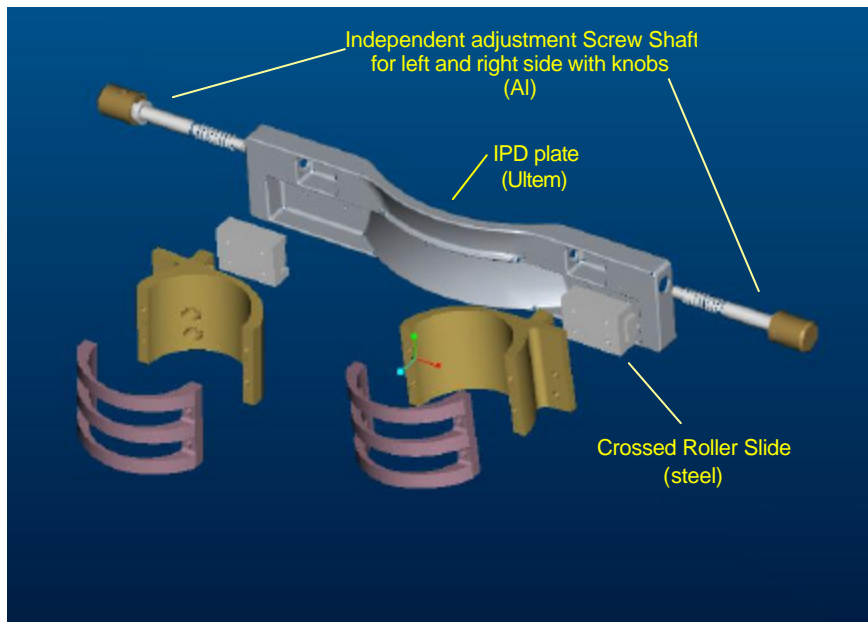


Figure 7. Exploded view of the IPD mechanism.

Up/Down

This adjustment is provided in the head-fitting system described later.

Focus mechanism is not necessary because optics provide 23 mm eye relief that allows use of prescription eyeglasses.

4.3.3. Design of Head fitting System and Main Body

Figure 8 shows the head fitting system that is used for this HMD. The raw form of this system is available of-the-shelf. This is a lightweight adjustable system that can be easily put on and

removed from the user head. This consists of durable plastic head straps that grip the head around the periphery and top. Figure 8 shows the system in its modified form that incorporates a sheetmetal lightweight custom frame to ruggedize the system and to integrate it with the rest of the HMD. This sheetmetal frame also eliminates the need for an overall HMD housing. This tremendously saves weight and cost. This frame can be easily fabricated at any sheet metal house without any special tooling. Another modification to this system is addition of a padded crown that distributes the weight of the HMD over a larger head area to provide comfort during extended use. This also improves balance and hence allows rapid head movements.

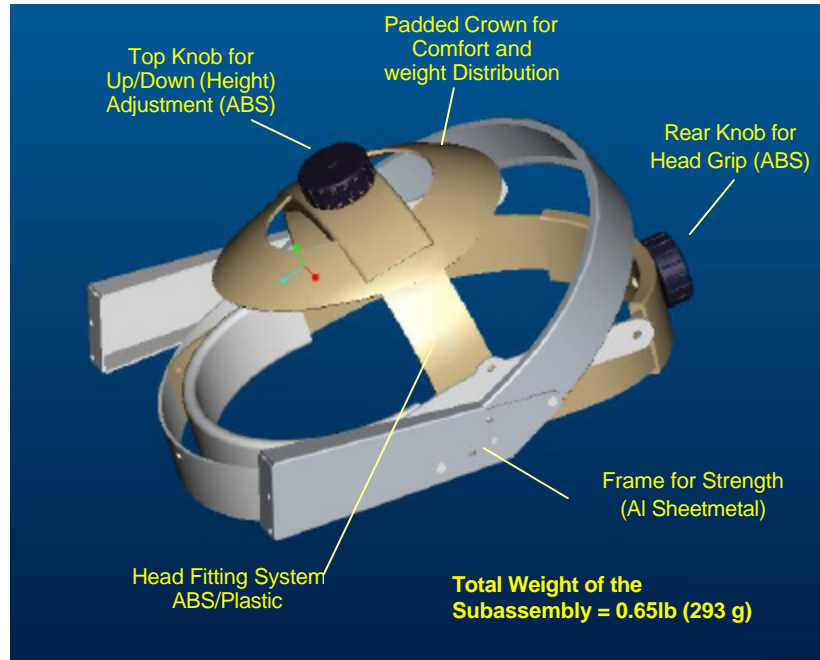


Figure 8. Head fitting mechanism of the PPHMD.

4.3.4 Miscellaneous Design

Since the cables are to be routed to the back to the HMD, have to be strain-relieved for safety, and a provision is needed for mounting a motion sensor (head tracker), a multifunctional “plate” was conceived that would be mounted at the back of the HMD frame to provide these capabilities. The plate is made of a heavier material such as Brass that could also effectively serve as a counterweight. Generally speaking, a heavier, well-balanced HMD is more desirable than a relatively lighter, poorly balanced one. Figure 9 shows the plate.

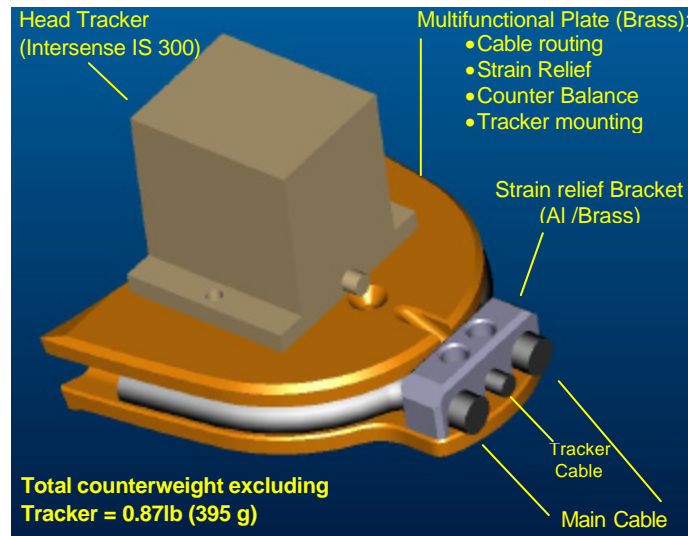


Figure 9. Multifunctional plate.

4.4 Electronics Design

The electronics design mainly constitutes designing a Video Control Unit (VCU) that provides video and power to the HMD, and also provides other necessary functions and adjustments that will be required during the actual operation of the system.

Each Microdisplay of the proposed HMD has an associated interface electronics board set. The companion interface electronics accepts VESA standard graphic input in either analog or DVI (Digital Visual Interface) digital video formats. Each interface board set occupies a volume of approximately 40 cubic inches. The design of the VCU includes:

- Two board sets mounted inside an off-the-shelf metal enclosure that is modified to the optimum size and provided with necessary cutouts to mount the various connectors.
- Two independent VESA standard graphic input in either analog or digital video formats (DVI-I) for stereoscopic viewing.
- Single VESA standard graphic input in analog video format for non-stereoscopic binocular viewing.
- A video pass-through capability to reproduce the video on an external monitor.
- One integrated 65 Watt AC/DC switching power supply that provides the required 12 volts to each board set.
- A brightness control circuit to control the brightness of the two displays with one analog control potentiometer. Each channel has a trim potentiometer to provide for an initial balance between the two displays.
- A PC-based software tool to independently configure the left and right interface electronics via a standard RS-232 serial link.
- A cooling fan to keep the VCU steady-state temperature under control.

5. Results

5.1 Microdisplay

Table I shows the specification of the FLCOS microdisplay used in the design.

Table 1. SXGA Microdisplay Specification

Display type	FLCOS, reflective mode
Spatial resolution	1280 (H) X 1024 (V) pixels
Active area	17.43mm (H) X 13.95mm (V)
Pixel pitch	13.62 μ m (H) X 13.62 μ m (V)
Fill factor / Aperture ratio	93%
Optical efficiency	>70%
Contrast ratio	200:1
Color technique	Color sequential
Color depth	24 bits (red 8; green 8; blue 8)
Operating temperature range	+10°C to +60°C
Storage temperature range	-40°C to +85°C
Input format	SXGA (1280 X 1024 pixels), 60Hz non-interlaced

5.2 Optical

Table 2 shows the optical specifications, Table 3 shows sizes and weights of various optical elements.

Table 2. Optical Specification Data

EPD	12 x 10 mm without the diffuser 17 mm round with high gain thin diffuser
Eye Relief	23 mm
Monocular FOV	80° (Horizontal) 68° (Vertical) 94° (Diagonal)
Overlap angle	60° (Horizontal)
Binocular FOV	100° (Horizontal)
Telecentricity	Yes
Optical Resolution	4.5 arcmin per pixel
MTF	20% at 36.72 lp/mm

Table 3. Size and Weight of Optical Elements

Element #	Diameter/Size (mm)	Weight (g)	Description	For elements numbers refer to Figure 2
1	59.5	14.251	Pancake Optics	
2	67.0	31.206	(Round)	
3	40	14.671	Projection Optics (Round)	
4	35.2	17.245		
5	31.5	13.701		
6	38	19.700		
7	40	10.896		
8	42	42.653		
9	26.83 x 26.83 x 34.4	73.721	Rectangular Prism Beamsplitter for illumination	
Total Weight		238 grams		

5.2 Mechanical

Table 4 gives overall HMD weight without and with the counterweight and the location of center of gravity in each case. Table 5 gives weights of the major components that form the HMD, and Table 6 shows HMD form factor size. These results are also illustrated in Figures 10 and 11, and 12.

Table 4. Overall Weight

Item	Weight	CG coordinates
HMD without counterweight (Fig 10)	1.03 Kg	(0, 3.2", 4.2")
HMD with counterweight (Fig 11)	1.42 Kg	(0, 3.1", 1.8")

Table 5. Major Components Weight

Item	Qty Per HMD	Weight	Total Weight
Opto-mechanical module	2	272 g	544 g
IPD Assembly	1	146 g	146 g
Head Fitting System	1	293 g	293 g
Counterweight	1	395 g	395 g

Table 6. Form-Factor

Parameter	Value
HMD size (figures 11 and 12)	14.2" (long) x 8.97" (wide) x 8" (high)
IPD adjustment range	55 mm to 75mm with 17mm exit pupil. Covers 95% percentile IPD among men and women across Caucasians, Asians, and African Americans.

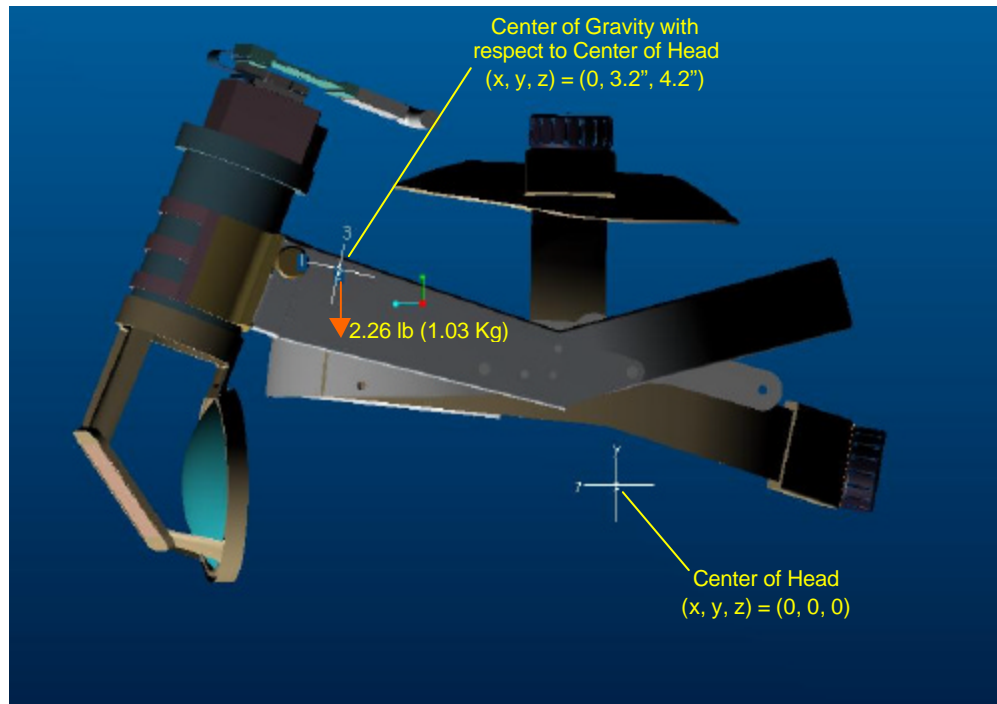


Figure 10. PPHMD weight and CG location not considering rear counterweight.

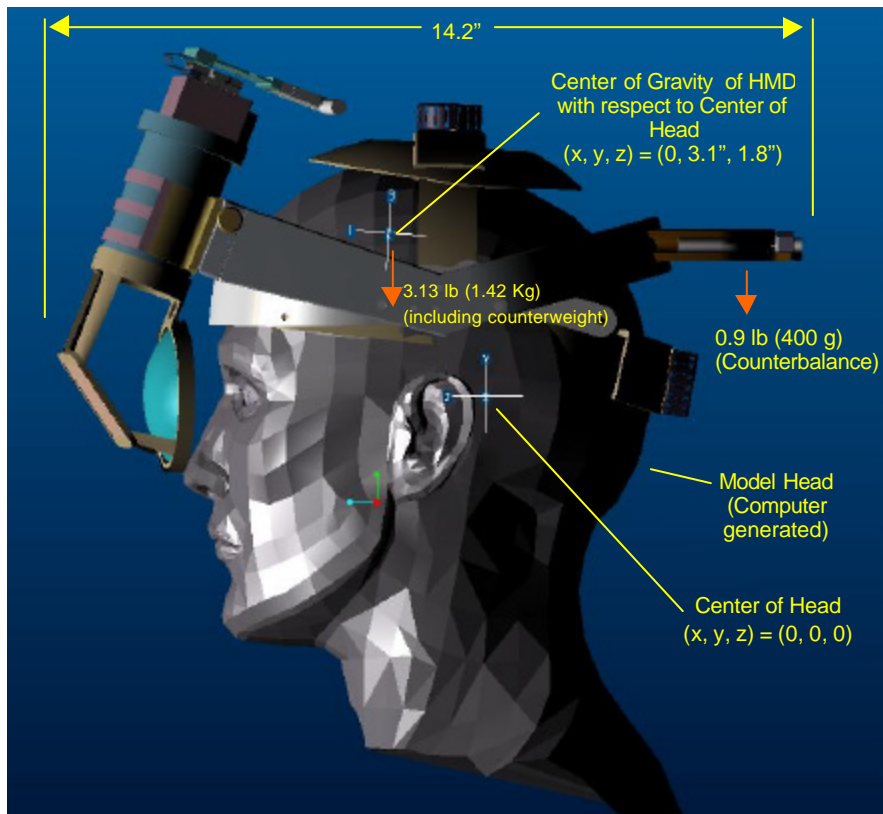


Figure 11. PPHMD weight, CG location, and size considering rear counterweight.

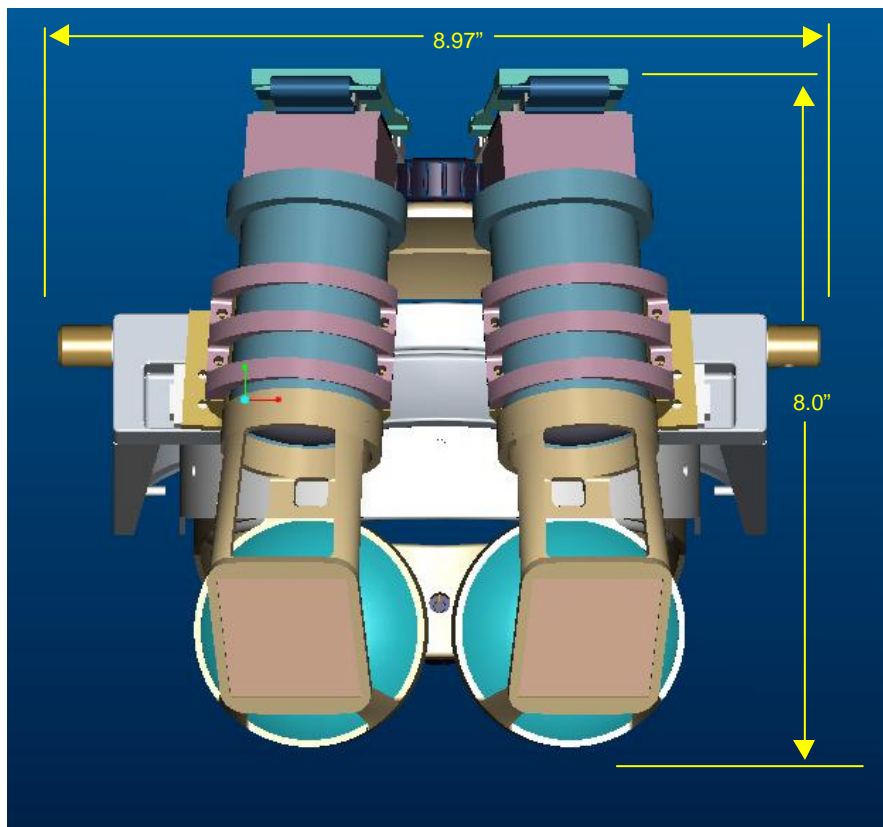


Figure 12. PPHMD front view and size.

5.3 Electronics

VCU

The VCU is completely designed and functional. It is 11"(wide) x 3.47"(high) x 10" (deep). It was demonstrated to NRL during their recent visit to NVIS, Inc. Figure 13 is a digital photograph of an actual fully functional VCU. This VCU is also being currently used with NVIS products like the Virtual Binocular SX and the upcoming nVisor SX HMD based on the same FLCOS microdisplay.



Figure 13. Actual VCU photograph.

In the current design, each channel in the VCU is connected to its corresponding microdisplay via a cable of copper wires of up to 6 meters in length. The interface on this cable consists of 11 analog/power lines and 14 twisted pairs of digital data transmitted via LVDS (Low Voltage Differential Signaling) circuitry. The LVDS interface represents an initial 67-bit bus before serial conversion. The use of the LVDS signaling reduces the number of wires in the interface between the electronics and the display.

Slip Rings

Using proven slip ring technology can solve the problem of connecting to a tethered HMD. This is researched in this phase. Slip rings allow continuous 360° rotation of the user while maintaining signal (video) and power connection to the HMD. There are two possible configurations for the rotating interface. The better connection point in terms of minimizing weight on the user is to put the rotating interface between the HMD and the video control unit (VCU). The VCU is static and easily connected to a video and power source. Unfortunately, the electrical interface between the VCU and the HMD is a high-speed digital bus with 102 lines of data, control and power. This is a large number of connections for a standard electrical slip ring device. However, there are fiber optic slip ring devices that would provide a solution to this problem. A fiber optic connection that serializes the data bus was previously discussed as a solution to the problem of long cable lengths between the VCU and the HMD.

The other configuration is to mount the VCU on the user and put the rotating interface between the video signal and power source and the VCU. This reduces the number of lines to three video lines, two sync lines and one power line and a return line. Electrical slip ring devices easily handle this. To maintain video signal fidelity, the bandwidth that must be maintained across the rotating interface is approximately 200 MHz for SXGA video. An example of a device that can provide the necessary performance is an industrial slip ring from the Endura-Trac family of the

Electro-Tec Corporation in Blacksburg, Virginia. The cost for the device is approximately \$2000. Electro-Tec manufactures slip rings that are used in CCTV applications and will customize their product for our application.

6. Discussions of Results

6.1 Optics

The design meets the important proposed goal of FOV. The goal for optical resolution of <3 arcmin/pixel was set during the time of the proposal. However, during design discussions with NRL, a few important things were learned specific to the targeted application. These were:

- A lower arcmin/pixel although desirable, could be sacrificed to maximize the FOV within practical.
- Vertical FOV should be maximized beyond the proposed 50°, and
- The binocular overlap region should be maximized for a wider stereoscope view.

The design accounted for all of the above and as a result the 3 arcmin/pixel was modified to 4.5 arc/pixel to meet the other more desirable goals.

The optics weight of the final design after replacing some of the glass elements by plastics can be about 200 grams per eye. Accounting for emerging technologies to replace the illumination cube (discussed under Section 8), the weight of the can further reduced to 100 grams per eye.

Before the inclusion of the diffuser as discussed in section 4.2, the designed exit pupil is a rectangular aperture of 12 mm horizontal by 10 mm vertical. Given the maximum diameter of the eye pupil of 3mm under photopic lighting conditions (lighting imposed by the microdisplay), the 12 mm by 10 mm exit pupil size of the optics allows an eye-swivel of $\pm 26^\circ$ azimuth and $\pm 21^\circ$ elevation without causing vignetting in the overall FOV. Vignetting refers to cutting of the bundle of light reaching the eye in this case by either the edge of optical elements or interfering mechanical structures holding the optics. Such large pupil size also allows a tolerance of ± 6.5 mm in IPD adjustment for different users. With the use of the diffuser and the consequently larger 17 mm pupil size, the swivel of the eye in the exit pupil is estimated to be $\pm 37^\circ$.

Resolution and MTF

Optical resolution is defined as the highest spatial frequency transmitted through the optical system, and in the case of a visual instrument like a HMD, the highest spatial frequency perceived by the user. However, such metric does not provide a full description of the generalized-resolution of the optical system because generally speaking a scene is composed of multiple spatial frequencies from background (lowest spatial frequencies) to objects (medium spatial frequencies) to details (highest spatial frequencies). Hence, we must consider how all the spatial frequencies are transmitted through an optical system. This is provided by the modulation transfer function (MTF) of the optical system. Furthermore, relevant to perceived image quality, the effective size of the pupil of the user is critical and is considered to be 3mm. MTF values can also be thought of as the perceived contrast of the spatial frequencies. The higher the MTF, the better the contrast. At least a 10% contrast at all spatial frequencies is desired with 20% across 85% of the FOV being a good goal.

Figure 14 shows that the MTF curves hold well up to 50 lp/mm, while the maximum resolution of the microdisplay corresponds to 36.7 lp/mm. Good image quality is achieved across the 12 mm x 10 mm pupil. The optimization of the optics was conducted using a 12 mm by a 10 mm overall pupil with a low weight assignment, as well as a 2-mm eye pupil specified on optical axis and at eight other decentered positions within the 12 mm by 10 mm pupil, each one with a weight proportional to its location away from the optical axis, given that the weight constitute a metric of probability of the eye behind the HMD during operation. Therefore, the MTF obtained and reported ensures that it will correlate well with the use of the instrument.

In phase I, the optimization procedure was limited to determining the feasibility. A greater level of optimization will be executed in phase II to fully balance the MTF performance across the overall field of view. This will bring all the curves within close proximity of each other. This will ensure that the final MTF will be at least 20% over the entire FOV.

To achieve good image quality with the smallest possible number of optical elements, a combination of traditional optics and diffractive optics is adopted in the design. The layout shown in Figure 2 consists of 9 elements, including 3 diffractive optical elements. In large production quantities, diffractive optical elements can be manufactured at extremely low cost. Thus DOEs are desirable for the standpoint of both weight and cost.

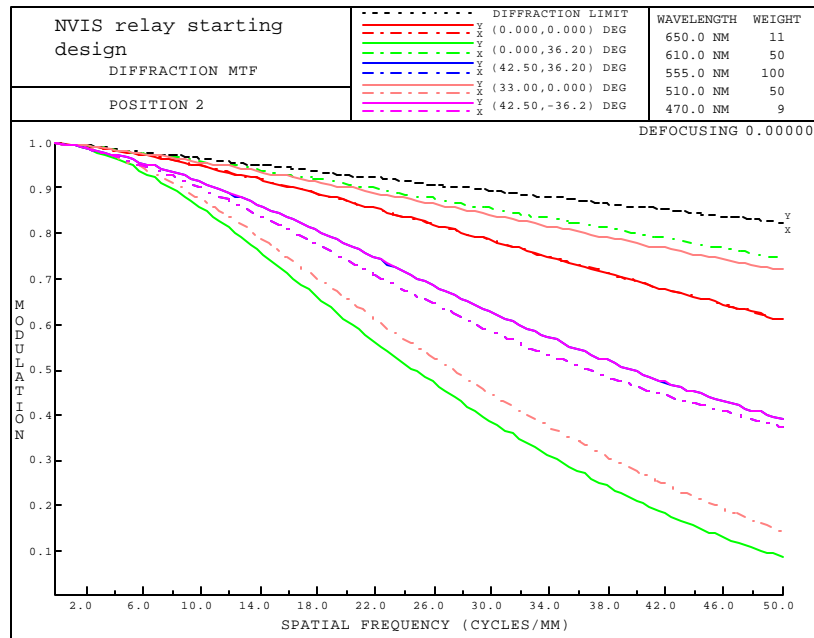


Figure 14. Modulation Transfer Function (MTF) with 3mm pupil.

Optical Distortion

Optical distortion is always critical in large FOV optics (i.e. >50 deg. diagonal) and certainly will be in the current 94° diagonal (monocular) design. However, because distortion is one of the optical aberrations that can be corrected in real-time (unlike blur aberrations such as spherical, coma, astigmatism) and since there is solution available to correct it in real time (by either using texture mapping algorithms or even using hardware solutions, e.g. sxW1 chip from Silicon Optix, Inc.), it was not necessary to correct it optically. This choice means reduction in the number of elements and hence the overall size and weight of the design.

If a rectangle is displayed on the microdisplay, the optics distorts it to produce a “pincushion” effect as shown in Figure 15. That mean the picture on the microdisplay needs to be pre-warped as a “barrel” as shown in Figure 16 to nullify the pincushioning effect introduced by the optics so that the final image is perceived as undistorted. Distortion introduced by the optics is 20% at the corners of the display. Since in the actual system a pre-warped (barrel) picture will be displayed on the microdisplay, a constraint that the distortion pattern fills the microdisplay size is applied to the optical design as presented in Figure 17 that also shows the actual distortion plot of the optics.

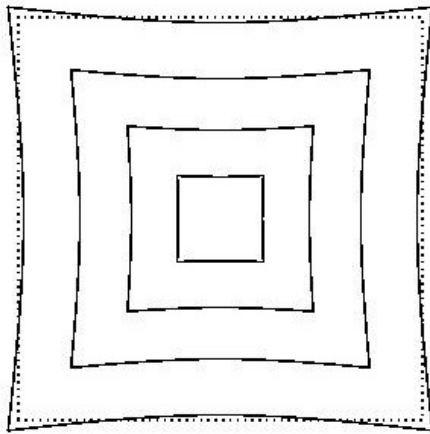


Figure 15. Pincushion Distortion

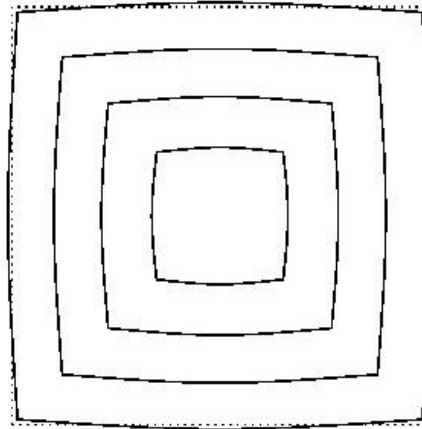


Figure 16. Barrel Distortion

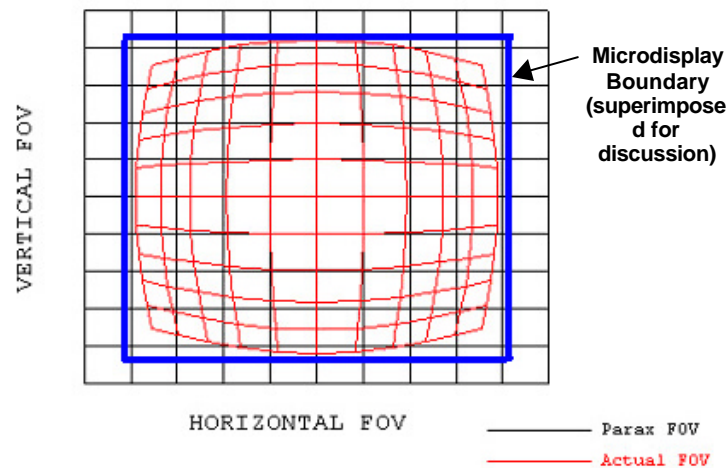


Figure 17. Actual distortion plot: symmetric about the optical axis.

6.2 Mechanical

The two opto-mechanical modules constitute more than half the weight (Tables 4 and 5) of the HMD, not considering the counterweight, which is mostly concentrated in front of the user (due to limitations in folding the optics). This makes the system relatively front heavy. Although in this configuration the designed HMD weight practically meets the proposed weight goal of 1 Kg, feedback from NRL confirmed it is really desirable to trade off weight with balance within reasonable limits. Based on the CG calculations a counterweight of about 395 g is set for the multifunctional plate to improve the balance.

The HMD design was tested using computer-generated models of a users head and a rifle. Figure 18 and 19 illustrates a model head wearing the HMD in aiming position with an M4 rifle. The form-factor of the HMD allows enough clearance between the HMD front optics and the rear sight of the rifle that enables war-fighter to effectively train wearing this HMD. Figure 20 shows the front view of the user with eye aligned with the rear sight of the rifle while wearing the PPHMD.

According to Marine Corps Reference Publication (MCRP) 3-01A, *Rifle Marksmanship*, normal eye relief for proper aiming is between two and six inches. This is the distance between the rear

sight aperture and the aiming eye. Figures 18, 19, and 20 use an aiming eye relief of approximately 5 inches.

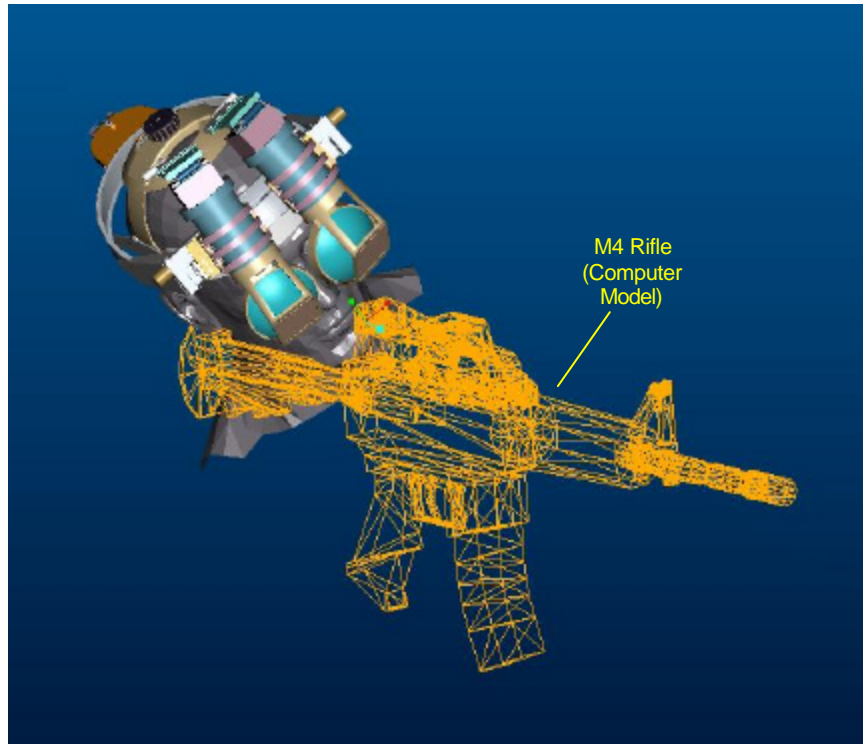


Figure 18. 3D view of PPHMD in relation with user in aiming position with M4 rifle. Projection optics is folded up and away from the rifle to provide normal aiming eye-relief for the user.

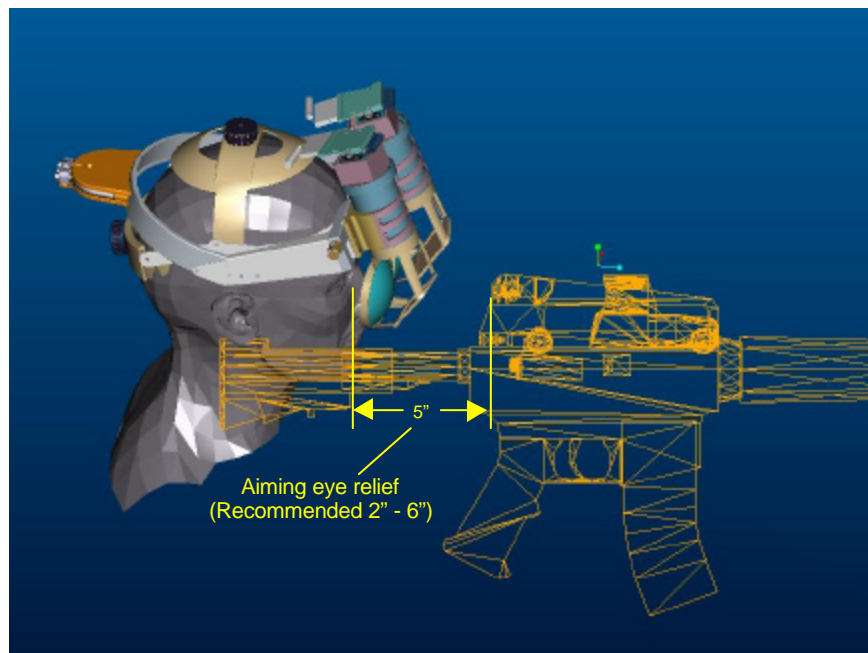


Figure 19. Side view of PPHMD in relation with user in aiming position with M4 rifle.

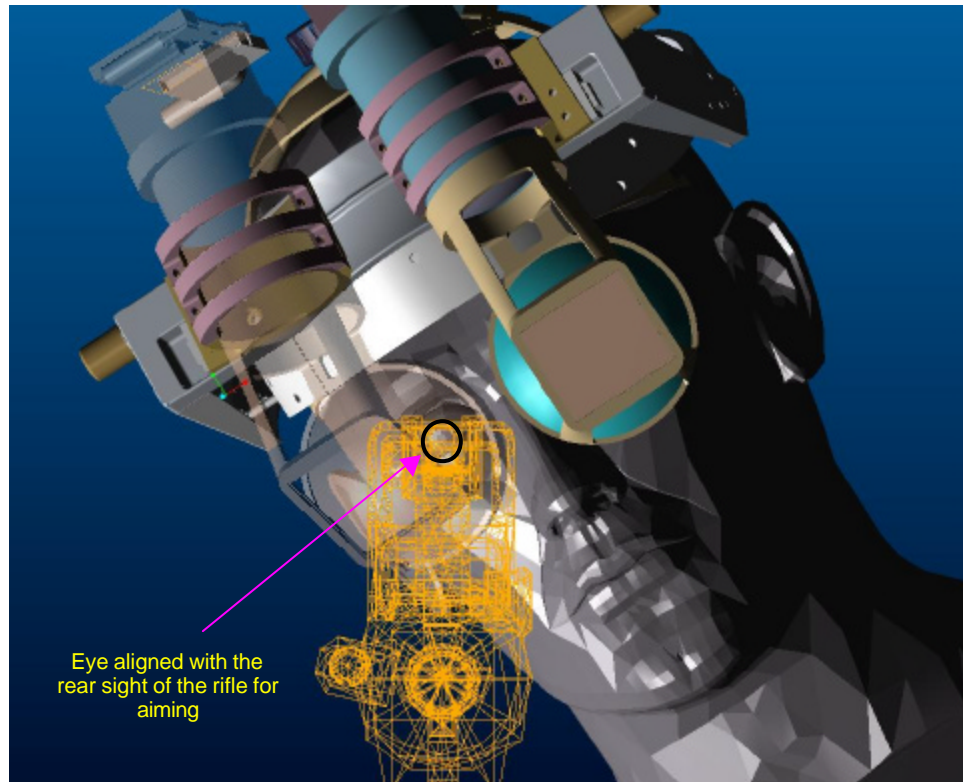


Figure 20. Front view showing the eye alignment with rear sight of M4 rifle while wearing the PPHMD

6.3 Electronics

To correct the geometric distortion (as explained in section 6.1) caused by the wide-angle optics, NVIS will incorporate off-the-shelf distortion correction circuitry into the final VCU design. These chips will compensate for the distortion introduced by the optics at the expense of overall pixel resolution. This will be implemented in electronics during Phase II.

As explained earlier the feasibility of the slip rings was researched in this phase. Off-the-shelf products exist that can also be customized for this application. This implementation will be proposed for phase II.

7. Other Investigations as Part of this Phase 1 STTR

7.1 Comparison of Pancake-Projection Optics with Conventional Pancake-Relay Optics.

This section quantifies the benefit of using DOE elements combined with a diffuser to minimize the overall optics weight. We showed in a previous analysis under Section 5.2 that the weight of the proposed optics for all glass elements will be less than 240g per eye with a predicted weight of 200g per eye when the design is optimized for plastic components.

Pancake-relay optics with a 17 mm pupil size, and a monocular 80°(H) x 68°(V) FOV was analyzed as shown in Figure 21. The overall weight was found to be 507 grams per eye. Thus, the approach proposed allowed to decrease weight by 50%.

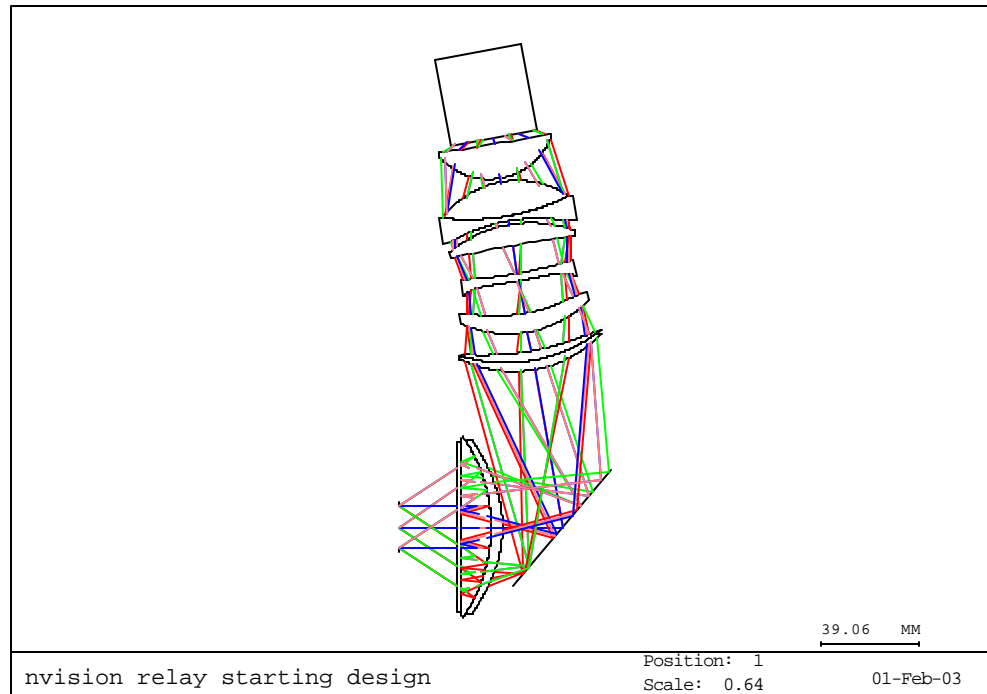


Figure 21. Conventional pancake-relay optics layout based on optical parameters set for PPHMD.

7.2 Investigation of large FOV with tiling optics

Originally, a tiled approach to produce a $80^\circ(\text{h}) \times 50^\circ(\text{v})$ monocular FOV was explored. This approach could potentially yield an overall $120^\circ(\text{h}) \times 50^\circ(\text{v})$ by optically juxtaposing the images of two microdisplays for each monocular channel, and superimposing the images of the two middle microdisplays of the binocular field.

Although this approach met the proposed optical specifications, feedback from NRL confirmed that maximizing the vertical FOV beyond 50° would be extremely beneficial to the CQB training application. With the original (tiling) approach:

1. Increasing the FOV beyond 50° became impractical due to limitations in folding techniques to achieve a tiled image, and
2. The form factor could not be improved effectively to accommodate rifle handling in the application (specifically the M4 rifle as that is being currently used by NRL). This is attributed to the optics requirements to achieve tiled images for a wide FOV requirement: large combining-prism, independent illumination and projection optics for the four microdisplays.

Figures 22 and 23 illustrate the relative orientation of the tiling optics and the four microdisplays with respect to a user in aiming position with an M4 rifle. It can be seen that this arrangement will likely compromise the aiming function of the user. Aiming eye relief of approximately 5 inches is kept here for comparison.

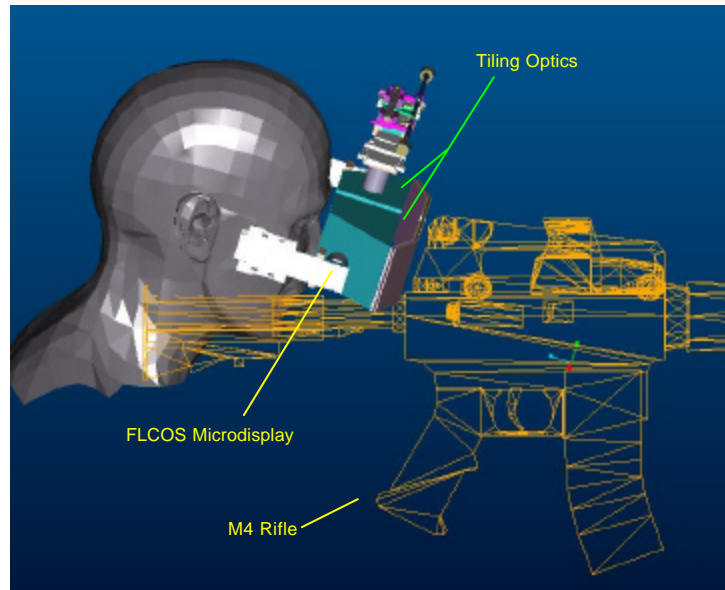


Figure 22. Side view of tiling optics in relation with user in aiming position with M4 rifle. Optics interference with rifle is anticipated at aiming eye relief of 5 inches.

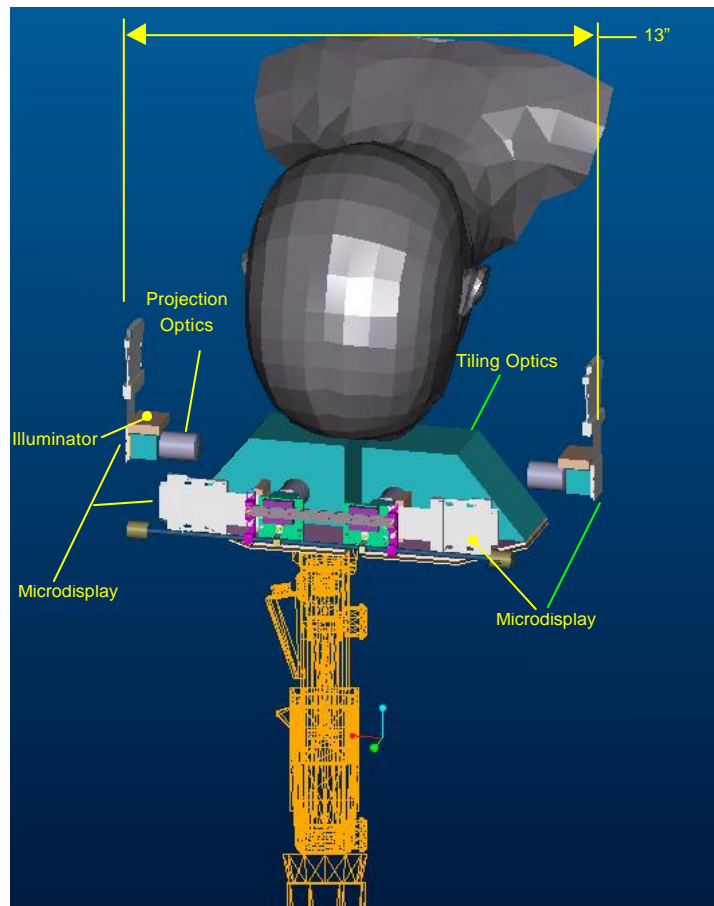


Figure 23. Top view of tiling optics in relation with user in aiming position with M4 rifle. Showing overall form-factor dictated by the optics and four microdisplays in tiled orientation.

8. Surveying of Emerging Technologies

We have identified two emerging technologies that can further benefit the goal of designing lightweight large field of view HMDs.

The first technology described below (section 8.1) will enable illuminating the LCOS display without the illumination cube which would lead to a significant reduction in the weight of the optics and hence of the overall system (i.e. total of about 150g for the optics and additional for the mechanical structure required).

A second technology described below (section 8.2) would enable yet a different illumination scheme that does not require miniaturization of any structure as described in the other approach. The technology is in the process of commercialization and could be available as soon as 6 months to a year from now. The current design could benefit from this technology in terms of weight and FOV.

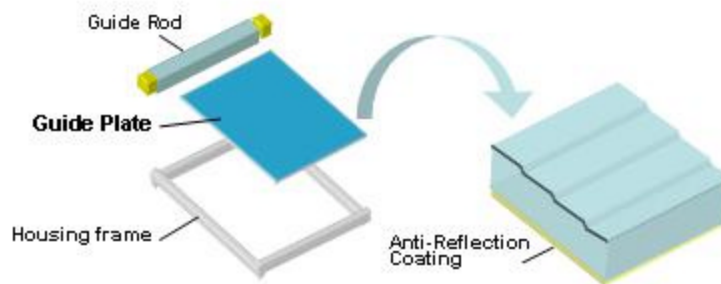
While the system proposed for phase II does not depend on these emerging technologies, such technologies provide a path to even further improvements in the current design.

8.1 Front Lighting Waveguide for Reflective Liquid Crystal Display (LCD)

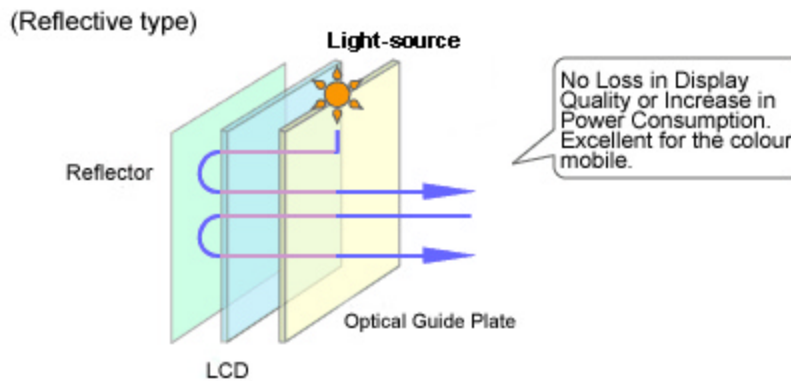
A novel method to provide illumination for a reflective LCD panel is to use a transparent light source in front of the panel. Because the LCOS is a miniature reflective display such technology can in principle be applied to the LCOS display as well. The technology has been recently applied indeed to the pocket PC. This technology is quite novel and has not yet been miniaturized so it can be applied as a front lighting scheme in LCOS displays for HMDs.

Illustrated in Figure 24 (a, b, c), this technology uses a unique structure of converting a point light source to a linear shape light source using guide rods. The linear light source is finally converted to a plane light source using a guide plate efficiently. Standard guide plate has equally spaced fine grooves. The ultra-fine grooving of the guide plate, several microns in size, can control the light pass without deteriorating the visibility. The anti-reflection film on the bottom side of the guide plate can prevent the degradation of its contrast (Figure 24(a)).

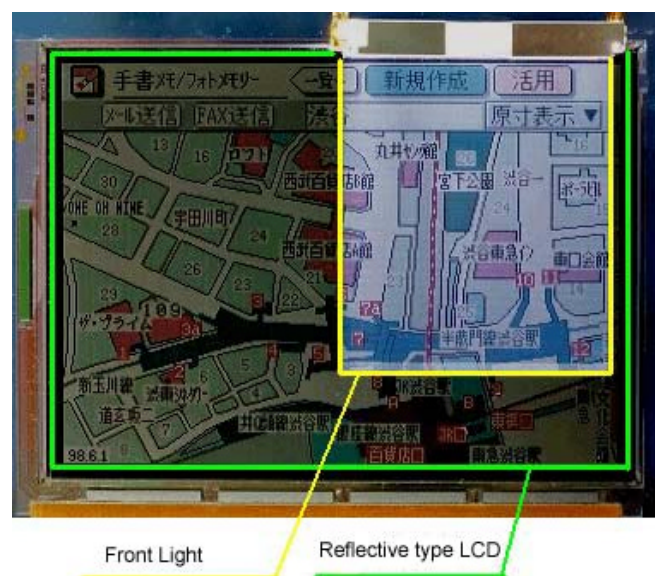
(Refer URL: http://www.minebea-ele.com/en/product/lighting/E_2000/E_2002.html)



(a) Converting a point light source to a plane light source



(b) Layout of the novel front light approach



(c) Example of how this front light is used; it is clearly demonstrated that the front lighting yields higher illumination performance

Figure 24. Front light scheme technology

8.2 Multidirectional Asymmetrical Microlens-Array Light Control Films (MAMA-LCF)

Another technology was recently developed to enhance the image brightness and contrast ratio of reflective liquid crystal displays. Dr. Rolland consulted Dr. Wu, Professor in the School of Optics/ CREOL, expert in the development of such systems, who confirmed the feasibility of this concept for this project. This technology is referred to as a "Multidirectional Asymmetrical Microlens-Array Light Control Films (MAMA-LCF) for High Performance Reflective Liquid Crystal Displays" – Huang et al., SID 02 DIGEST, 870-873 (2002), and is illustrated in Figure 25. The MAMA-LCF which is constructed with asymmetrical microlens arrays, leads to a ~5x gain in brightness over the MgO standard white and 12:1 contrast ratio for color STN-LCDs, 10x gain and 11.5:1 contrast ratio for PDLC, and 9x gain over the conventional Ch-LCD.

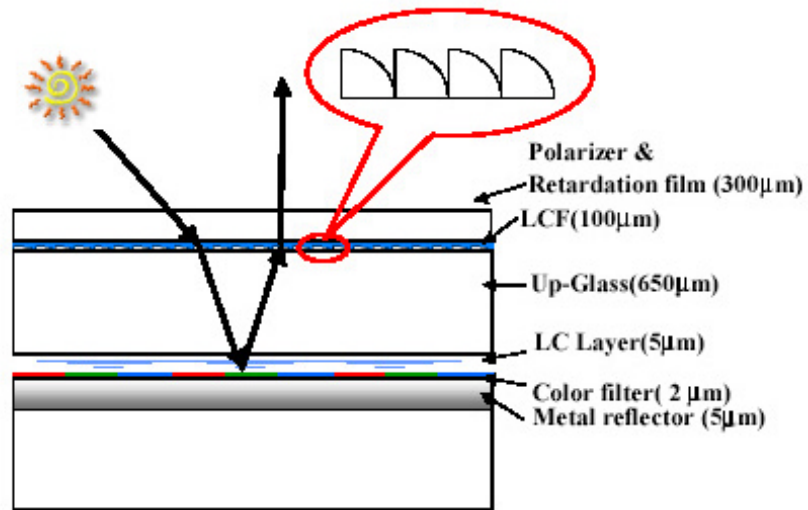


Figure 25. Configuration of a reflective LCD using a MAMA-LCF

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Contract No.: N00014-02-M-0229
Navy Small Business Technology Transfer Program
5 Page Phase II Plan
STTR Topic # N02-T005

Period covered: July 2002 Through February 2003

An Improved Head-Mounted Display For Virtual Reality

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Introduction

The following 5-page plan outlines the course of action the NVIS team will take to successfully execute Phase II of STTR contract N02-T005, “An Improved Head-Mounted Display for Immersive Virtual Reality”, with an emphasis on producing a successful commercial product as a result of these efforts. The NVIS team consists of personnel from NVIS and the University of Central Florida’s School of Optics/CREOL, as well as individuals and companies hired to assist in the effort. This plan will illustrate how this team of engineers and scientists will take the completed optical design from the Phase 1 base effort and turn it into a complete, form-fit-function prototype for the Navy’s *Close Quarter Battle* (CQB) urban combat training system. This plan will also indicate how NVIS will leverage its experience in bringing immersive display technology into broader commercial and military markets beyond the scope of this STTR, thus laying the foundation for a successful Phase III effort.

Phase II Objective

The Phase II objective for NVIS will be to deliver two working prototypes based on the design described in the associated Phase I Final Report. Both prototypes will consist of a head-mounted display device with an associated video control unit (VCU). The first, or *Stage I* prototype, will be a preliminary prototype based on the optical and mechanical design presented in the Phase I Final Report. After field-testing and analysis, NVIS will build the *Stage II* final prototype with any necessary refinements to the optical and/or mechanical design.

In addition to the engineering effort associated with Phase II, NVIS will leverage its experience in marketing immersive display technology to appeal to customers and applications outside the scope of this STTR. This will include a business plan that exposes the product to both military and industrial users. This will entail an elaborate web presence, trade show events, and print advertising.

Phase II Work Plan Summary

The following table summarizes the tasks to be accomplished to meet this objective. The cost estimate and preliminary schedule are in the last section of the plan.

Task
Optical and industrial engineering <ul style="list-style-type: none">• Optical engineering analysis to prepare optical design for prototype production• Design considerations for VCU placement and cabling, including slip-ring design (or similar) for routing cables• Interim Design review with NRL• Complete outer housing design and HMD adjustments, including adjustable overlap• Final design review with NRL
Prototype fabrication <ul style="list-style-type: none">• Optical prototyping and test• Build Stage I prototype• NRL field test and analysis• Build Stage II final prototype• Final NRL demonstration

Table 1: Task List

Optical Engineering

The Phase I Final Report submitted by NVIS summarizes the HMD design developed during the Phase I work effort. This design meets the fundamental requirements for the new HMD and will be the starting point for NVIS to move forward into Phase II with production of a working prototype. Before prototype

production begins, however, NVIS would like to carefully review design options with the customer and keep them informed of our decisions affecting the final product. These issues may include:

- Folding of the optics to minimize inertia and improve balance
- Optimize optical design, i.e. set elements to correct geometry and perform tolerance analysis, and material selection to optimize performance and weight
- Investigate using a moderate amount of diffusion to increase pupil size while not increasing size/weight

Industrial Engineering

The industrial engineering tasks consist of those activities that integrate the HMD optics, mechanics, and electronics into a complete package that is both functional and easy to use. A well-engineered HMD must be comfortable and provide a range of adjustments to accommodate different users. In the case of the CQB application, the user must be able to move rapidly and operate a simulated rifle during training. The task of designing an HMD that meets these objectives will be handled by NVIS with the help of the industrial design firm ION Design (see *Key Personnel section*). These tasks will include:

- HMD material selection to reduce weight, increase strength, and/or lower costs
- Outer housing design, styling
- Cable and wire routing solutions to accommodate the customer's unique training environment, including the use of slip-rings or a similar solution to provide freedom of movement during training

Through our discussions with the technical team at NRL, NVIS learned that while a large FOV is desirable, a large *overlap region* is equally important to provide sufficient stereoscopic viewing performance. Since reducing the overlap is a common technique used to increase total FOV, NVIS will design the HMD with *factory-adjustable* overlap, thereby allowing the user to experiment with different HMD FOV/overlap configurations and carry out meaningful experiments with a single unit.

Prototype Fabrication

The first HMD prototype will be based on the design as summarized in the Phase I Final Report. It will be assembled using parts made with *Rapid Prototyping* techniques ranging from conventional machining to stereo-lithography (SLA) and soft tool molding. The three-dimensional CAD output from our design software may be read directly by systems that drive SLA machines and robotic control programs that generate tool paths for CNC (*Computer Numerical Control*) machines. This will dramatically reduce the time required to build a functioning prototype.

The completed system will be delivered to NRL for thorough field-testing and analysis to study multiple HMD attributes including FOV, exit pupil, image quality, ergonomics and eye-relief.

Following the field-tests from the Stage I prototype, NVIS will develop the Stage II (pre-production) prototype with modifications that can include:

- Injection molding techniques to reduce weight of plastic components
- Incorporating moderate amounts of optical diffusion to increase exit pupil size while not increasing optics weight and size
- Increase/decrease total FOV and/or overlap (with tradeoffs)
- Any other suggestions currently unforeseen by either NVIS or NRL

In addition to creating an improved HMD design and allowing NRL to take possession of two prototypes, the two stage approach to the prototype process allows NVIS to demonstrate the Stage I prototype to other components of DOD to generate interest and financial support early enough for a Phase III award (see business plan, below).

NVIS engineers have been developing immersive displays with these techniques for more than 5 years. Minoo Bablani, the Principal Investigator for the STTR project, managed the HMD production program for n-vision to deliver more than 100 systems to Disney Regional Entertainment for their DisneyQuest attractions in Orlando and Chicago. The NVIS team will apply this knowledge and experience to

economically manufacture a form-fit-function prototype for the completion of Phase II and prepare the design for transition to production later in Phase III.

To accommodate lead times associated with custom tooling, interim design reviews with manufacturers, assembly and test, NVIS will require approximately 6 months to build and test the Stage I prototype. An additional 6 months will allow NVIS to incorporate final design revisions and deliver the Stage II (pre-production) prototype.

Optional Work

(Phase II Option)

We propose as an option to Phase II to research new illumination schemes for reflective LCDs. Such schemes could contribute to further lighten the currently proposed wide FOV HMD. The investigation will be based on the analysis of two emerging technologies, one is a light pipe that allows illumination without the need for a cube in front of the display, and the other is a microstructure that helps redirect the light from a side illumination to a front emitting configuration. Again such a structure removes the need for the illumination cube, which in itself account for a significant part of the size and weight of the optics. Both schemes were briefly described in the final report for Phase I. In this investigation, Dr. Rolland proposes to collaborate closely with Dr. Wu of the School of Optics/CREOL, former senior scientist at Hughes/Raytheon, who is a recognized expert in such emerging LCD technologies.

Business Plan

History

The NVIS engineering team designed and manufactured the Datavisor family of head-mounted displays from n-vision in the 1990's. Systems were delivered in diverse applications including flight simulation/training, automotive design, medical visualization, research, and entertainment and the customer base included Lockheed, Raytheon, Boeing, BMW, DaimlerChrysler, Volvo, NASA, Walt Disney, and universities and military organizations worldwide.

NVIS was founded in March 2002 and continues to develop and market high-resolution 3D immersive display systems for use in industrial, scientific, and defense applications. The company continues to evolve the concept of a commercially available HMD device that achieves razor-sharp visual acuity in a package that is robust and easy to use. Commercial products developed by the NVIS team since March 2002 include the Monoscope SX, Virtual Binoculars SX, and the new nVisor SX HMD. The company also adapts its commercial products for customer-specific requirements and provides software engineering and electro-optical engineering services to clients in government and industry. An example of one such product is a simulated laser range finder designed to train soldiers to operate a real MELIOS device (Mini Eyesafe Laser Infrared Observation Set). Current customers of NVIS products include the Army, Navy, Mitre Corporation, Computer Sciences Corporation, Japan Defense Agency, Dornier, and Kongsberg Norcontrol Inc.

Developed initially for high performance military applications, our products have been successfully adapted for a wide range of non-military applications including industrial design, research, medical, and entertainment applications. NVIS products are sold worldwide with active distributors in Japan, Germany, France, and the United Kingdom.

Commercialization Strategy

NVIS plans to follow the same successful marketing and sales strategy for the HMD developed under this contract. This includes industry trade show exhibits such as SIGGRAPH, Medicine Meets Virtual Reality (MMVR), and I/ITSEC as well as print advertising in military and medical training/simulation journals.

Current NVIS customers have already indicated an interest in a new wide FOV HMD. Bill Walker from the Naval Air Warfare Center (NAWC) in Orlando, FL, has approximately 10 Datavisor HiRes HMD systems currently in use in the Virtual Environment Submarine (VESUB) and Conning Officer Virtual Environment (COVE) projects. His attached letter was an email he sent to NVIS describing the Navy's interest in a new, wide FOV, immersive displays.

NASA in Johnson Space Center currently uses three Datavisor 80 HMDs to train astronauts for their spacewalk application. The Datavisor 80 offers approximately 100° H x 50° V FOV, and roughly 800 lines of resolution in a form-factor weighing more than 4.5 lbs. NASA purchased these systems for \$105k each. The HMD being developed for this STTR will have more FOV, resolution, and weigh less (see Final Report for details). The estimated retail price will be approximately half that of the Datavisor 80 system. By all accounts, the new STTR HMD will be a technical and economical improvement over previous generation systems.

Both NAWC and NASA have requested a product demonstration of the new system as soon as prototypes are available (no funding can be allocated by either agency until a system is fully operational and demonstrated). The evaluation team may freely contact representatives from either NASA or NAWC to discuss their future interests in NVIS products and HMDs in general:

- NAWC: Bill Walker (407) 380-8287, william.h.walker@navy.mil
- NASA: David Homan (281) 483-8089, dhoman@ems.jsc.nasa.gov

In addition to traditional sales and marketing efforts, NVIS will continue to strengthen its web presence. We plan to tie together common elements of successful HMD applications worldwide to help customers and industry identify which applications truly benefit from immersive display technology, and how. The web site will expand to feature articles from customers using NVIS equipment, covering the successes and challenges they've encountered while developing their applications. This effort is aimed to promote a better understanding of how to implement professional VR equipment into a more meaningful context and ultimately attract more customers to NVIS products.

Key Personnel Summary

NVIS will maintain the same engineering team from Phase I into Phase II, again lead by the same Principal Investigator / Project Manager Minoo Bablani. Mr. Bablani will be responsible for coordinating efforts among engineers at NVIS and the School of Optics/CREOL. He will also manage the individuals and companies hired by NVIS to assist in specific tasks including industrial design and manufacturing. Mr. Bablani will execute this role with the experience he has gained from managing multiple immersive display product life-cycles including the n-vision Datavisor products and the HMDs delivered to Disney Regional Entertainment as well as more current NVIS products such as the new nVisor SX HMD.

Dr. Jannick Rolland will again lead the team at UCF/CREOL as the Principle Researcher on the optical design for the HMD project. Jannick Rolland received a diploma in Optical Engineering from the Ecole Supérieure d'Optique in Paris in 1984, and a Ph.D. in Optical Science from the University of Arizona in 1990. Since 1990, she has made multiple contributions to the field of Virtual Environments as a whole not only in the design of novel HMDs, but also in the design of optical tracking probes and associated algorithms, optical motion capture for augmented reality research which was featured in Scientific American in April 2002, algorithms for calibration and registration in augmented reality research, and the development of software for perception studies in virtual environments. In addition to her numerous publications and contributions to optical research for 3D immersive display technology, Dr. Rolland has gained valuable knowledge from her hands-on experience at UCF where she has also manufactured complete head-mounted display systems based on her research.

NVIS will continue to work with Mr. Paul Weissman from Optical Resolutions, Inc. Mr. Weissman has proved an invaluable resource in guiding the NVIS team throughout our Phase I work effort. As both a world-class designer and an engineer with more than 20 years of experience developing near-eye optics, Mr. Weissman will offer the NVIS team indispensable advice and solutions as we move the product concept from design to prototype.

To develop a product that is both practical and appealing to users in the target application and other markets, NVIS will focus a substantial portion of the Phase II work effort on the industrial design process. To assist in this task, NVIS will hire ION Design.

Facilities and Equipment Summary

NVIS maintains an array of equipment at its headquarters in its Reston, Virginia office to help execute the design and fabrication of the Phase II prototype. This equipment includes:

- 3D CAD and modeling software
- Optical design and analysis software
- Optical alignment fixtures
- Electronic test equipment

The forthcoming Phase II proposal will contain a detailed list of hardware and software that will be used in the prototype development.

Cost Estimate and Schedule

Table 2 summarizes our preliminary cost estimates for the Phase II Base Effort and Option. Figure 1 provides a preliminary schedule for both the Phase II Base Effort and the Option.

Phase II Base Effort – Prototype Development			Phase II Option – Alternative Illumination		
Optical engineering	\$90,000		Optical engineering	\$30,000	
Industrial engineering	\$90,000		Electronic engineering	\$20,000	
Optical prototyping	\$100,000		Opto-mechanical	\$12,000	
Mechanical prototyping	\$135,000		Prototyping	\$15,000	
Misc (admin, travel, etc)	\$20,000		Fee (profit)	\$5,000	
Fee (profit)	\$30,000				
TOTAL	\$465,000		TOTAL	\$82,000	

Table 2: Cost Estimates

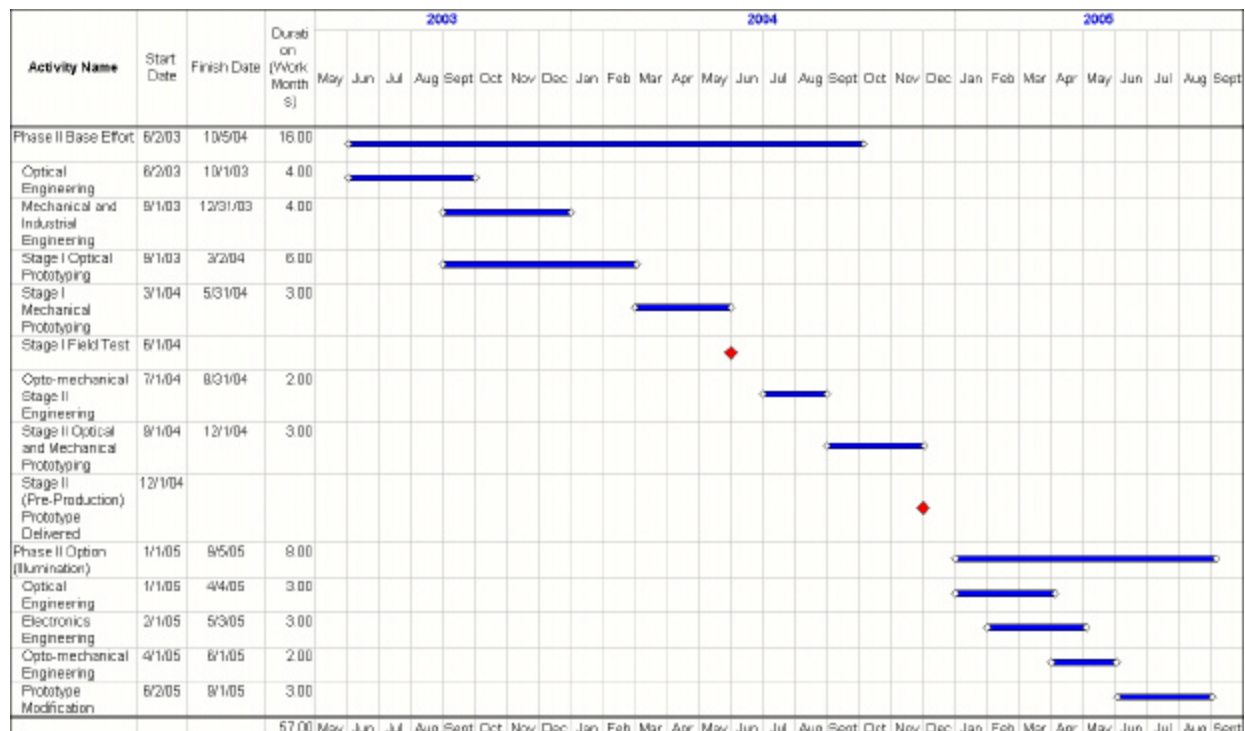


Figure 1: Preliminary Schedule

The forthcoming Phase II proposal will detail a DCAA approved cost summary capturing all relevant cost categories including G&A, overhead, labor, materials, and profit.